Journal of Forestry Research (2013) 24(4): 691−698
DOI 10.1007/s11676-013-0365-6

ORIGINAL PAPER

A site dependent top height growth model for hybrid aspen

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Received: 2012-01-17; Accepted: 2012-12-09

Abstract: In this study height growth models for hybrid aspen were developed using three growth equations. The mean age of the hybrid aspen was 21 years (range 15−51 years) with a mean stand density of 946 stems ha^{-1} (87−2374) and a mean diameter at breast height (over bark) of 19.6 cm (8.5−40.8 cm). Site index was also examined in relation to soil type. Multiple samples were collected for three types of soil: light clay, medium clay and till. Site index curves were constructed using the collected data and compared with published reports. A number of dynamic equations were assessed for modeling top-height growth from total age. A Generalized Algebraic Difference Approach model derived by Cieszewski (2001) performed the best. This model explained 99% of the observed variation in tree height growth and exhibited no apparent bias across the range of predicted site indices. There were no significant differences between the soil types and site indices.

Keywords: top height; farmland; hybrid aspen; site index; soil types; stands; total age; soil type

Introduction

Hybrid aspen trees have been extensively studied in Sweden, Finland, Norway, Denmark and the Great Lakes Region of the USA (Yu et al. 2001; Karačić et al. 2003; Tullus et al. 2012). Hybridization between the European aspen (*Populus tremula* L.) and the trembling aspen (*Populus tremuloides* Michx.) was first described at the beginning of the 1920s in Germany (Wettstein 1933). The first artificial crosses between European and trembling aspen in Sweden were undertaken in 1939 (Rytter & Stener 2005) with the earliest cultivation of this hybrid aspen being achieved at the end of the 1930s (Johnsson 1953, 1976; Langhammer 1973). Seedlings used in plantations and trials are a mixture of clones (European aspen growing south of lat. 60° N. in Sweden and trembling aspen at lat. 45−50° N. in USA) based on material sampled in 1939−1960 (Johnsson 1953; Stener 2002; Tullus et al. 2012). Today the owners are offered among others; "Ekebo mix", which is improved from the 1939−1960-material and a Finnish clone (Stener 2002; Rytter et al. 2011).

Results from Nordic trials on hybrid aspen stands established between 1940 and 1960 (Tullus et al. 2012) showed mean annual increments (MAI) between 12 and 17 $m^3 \cdot ha^{-1} \cdot a^{-1}$. The second generation of hybrid aspen, similar to the parent species, exhibits rapid establishment and fast growth: 50,000 to 100,000 suckers per hectare after cutting (Rytter 2006). In a German study (Liesebach et al. 1999), the number of suckers per hectare established after harvesting the first plantation (10 years) was 165,000 and after the second rotation (10 years) the number had increased to 215,000.

Site index curves are widely used by foresters for site quality characterization and potential productivity estimations (Hägglund 1981). The use of site index curves is based on the findings that a correlation exists between stand height and total volume production (Beaumont et al., 1999) and on areas having a good site quality the site quality is high (Bailey & Clutter 1974; Clutter et al. 1983). Site index has historically been defined as the top height of a stand at a predetermined age (Clutter et al. 1983). The top height is the arithmetic mean height of the 100 $trees \cdot ha^{-1}$ with the greatest diameters (Hägglund 1981). Diameters of individual trees can be measured easily. Especially the average height growth of the dominant trees is less affected by thinning operations (Bailey & Clutter 1974; Clutter et al. 1983) but also less affected by stand density (Monserud 1984). The models may be a first step towards assessment of stand volume production.

Traditionally the site index base age is fixed as an age lower than the rotation age. However, modern use of dynamic equations allows for the use of any ages a base age or reference age along with corresponding to them heights directly without converting the actual measurement to a fixed-base-age site index. Dynamic equations must fulfill specific requirements (described by Borders et al. 1984): (1) pass through the origin, (2) height equals site index (SI) at base age, (3) base age invariant curves and (4) have a separate upper height asymptote.

Bailey & Clutter (1974) formalized the name of "the properties

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of the Algebraic Difference Approach method (ADA)" as pertaining to substitution of a varying parameter by its initial condition solution, and the property of "base-age invariance" achieved through the covariance analysis fitting method. The earlier pertains to an algebraic operation resulting in a dynamic equation, while the later pertains to a method of parameter estimation of site index models. Cieszewski & Bailey (2000) has presented the Generalized Algebraic Difference Approach method (GADA). The approached model is more flexible to describe complex polymorphism of growth than the ADA model. GADA is widely used when constructing index curves: (Eriksson et al. 1997; Kiveste & Kiveste 2009; Nord-Larsen et al. 2009).

Site index curves for trembling aspen and European aspen have been reported (Payandeh 1974; Johansson 1996; Chen et al. 1998) but there are few site index curves published for hybrid aspen in Europe. Jacobsen (1976) presented dynamic equations for hybrid aspens growing on farmland in Denmark. Three curves (Bon I-III) were derived, indicating heights of 22, 17 and 13 m at 20 years of total age. The culmination of growth (CAI) was stated as 15−20 years.

The objective of this study was to evaluate different existing site index models for constructing site index equations for hybrid aspens growing on farmland. The equation should be used for site quality characterization and potential productivity estimations of hybrid aspens. A minor aim was to study the influence of soil type on the level of site index. The final recommended site index curves are aimed to be a tool for management of hybrid aspen stands.

Materials and methods

Sampling of trees and stand characteristics

Growth data were collected from 27 stands of hybrid aspen growing on farmland in Sweden, situated between latitudes 55º and 60º N. (Fig. 1; Table 1). The origin of the hybrid aspen was not known as the owners had not noted the hybrid crossing (clone). However according to the hybrid aspen plant distributors the commonly used origin at the planting period was a clone mix based on the material sampled during 1939 to 1960 (Johnsson 1953). The age of the stands ranged from 15 to 51 years and the stem number ranged from 87 to 2,374 (Table 1). The area of the stands varied between 0.10 and 1.00 ha. A sampling plot was marked out in the centre of the stand with 3 m to any edge in order to avoid edge effects caused by factors such as wind, open areas, ditches and shading by adjacent stands. The mean number of stems per hectare was based on the number of stems counted on the plots (0.07−0.10 ha). Some of the hybrid aspen stands had been thinned previously. The diameter at breast height (DBH) of all aspens on the plot was measured by cross callipering (Table 1), and the arithmetic mean diameter, 19.6 ± 6.5 (8.5−40.8), was calculated for each of the stands. For calculation of mean height in the hybrid aspen stands, 19.9 ± 4.2 (10.4−29.6), a statistical regression model for each stand was made. The height and diameter for 9 trees in two subsample plots each was measured. The two subsample plots (3 trees by 3 rows close to each other) were systematically located, e.g. the first measured tree was the fifth tree in the third row. The other subsample plots started in the opposite part of the stand area diagonal to the first plot. Then a regression model for each stand describing the relation of height to diameter was made. The rooting depth was >30 cm.

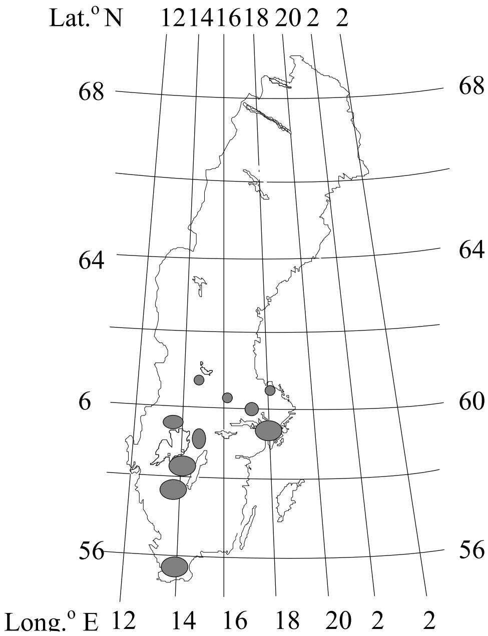

Fig. 1 Locations of the 27 sampled hybrid aspen trees growing on abandoned farmland in Sweden

Table 1. Summary statistics of height, age, diameter, stem number and basal area for stands and plots

Variable	Unit	No. localities/ plots	Mean	Std. Dev.	Minimum	Maximum
		Stand characteristics				
Stand size	m^2	27	1921	1960	800	10000
Height	m	27	19.9	4.2	10.4	29.6
Age	years	27	21	8	15	51
Diameter	cm	27	19.6	6.5	8.5	40.8
Stem number	stems ha^{-1}	27	946	545	87	2374
Basal area	$m^2 \cdot ha^{-1}$	27	23,6	10.2	7.6	51.1
		Plot characteristics				
Plot size	m^2	40	1575	1185	700	5000
Height	m	40	22.0	4.4	14.8	30.5
Diameter	cm	40	28.0	8.3	13.2	44.0

In the study one to three dominant trees were sampled from each of the 27 stands according to Fries (1964) who recommended up to three trees should be sampled. The trees were also assessed for damage, stem straightness and leader type (single vs. double or broken). The trees chosen for sampling (40 hybrid aspens), were felled with a cut as near to ground level as possible in order to facilitate measurement of height (m) and DBH

(cm). Mean height of the sampled trees was 22.0 ± 4.3 (14.8–30.5) m and a mean diameter of 28.0 ± 8.3 (13.2–44.0) cm. Cores from the stem were then taken at points representing 1, 10, 20, 30, 50, 70, and 90 % of the tree height and at breast height of 1.3 m. Documentation was available providing information on tree age. The total age is the sum of the age of the seedlings (1-2 years) at the time of planting and the documented age.

Soil sampling

Two soil samples were taken at random in each stand to a depth of 30 cm and the mean texture of the sampled layer was determined. Soils were classified in the field as tills or sediments (Johansson 1999) according to Ekström (1926) and then by particle size in the laboratory. The particle size distribution was determined using a mechanical sieving method (English and German standard), and soil types were classified as follows: a) sediments - gravel (20–2 mm), coarse sand (2-0.2 mm), fine sand (0.2–0.02 mm), silt (0.02-0.002 mm), or clay (<0.002 mm); b) tills - gravel, sandy, fine sandy, or silty; and c) organogenic soils - moorland peat or moss peat. Although the soil samples contained particles of different sizes, their type designation was based on the most frequent size characteristic, together with one or two soil prefixes associated with other less frequent soil types. Clay soils were then classified based on their percentage clay, as follows: light clay (13%–29%), medium clay (30%–40%), heavy clay (41%–60%), and till clay (13%–60%). The soil profile was analyzed and the mineral soil type recorded for all stands. Among the 27 stands 13 grew on light clay, six on till soils (sandy silty tills and light clay tills) and six on medium clay soils. The mean site index (H_{20}) for hybrid aspen stands growing on a specific soil type was calculated. The site index means for these soil types were: light clay 20.3 m, medium clay 18.6 m and tills 18.8 m.

Construction of site index curves

In artificial regenerations, such as hybrid aspen planted on farmland or forest land, where all trees are of the same age and the total age is known, the use of top height over total age is preferable (Elfving & Kiviste 1997). According to Monserud (1984) and Newberry (1991) the height of the site trees as index age is either observed or can be estimated with reasonable accuracy for each plot in a stem analysis study. The “true” height at sectioning point might be slightly underestimated at the determining age. This underestimation will be half the section (Carmean 1972), but this underestimation is of minor importance (Eriksson et al. 1997) and is not taken into consideration in the present study.

A data set was collected for each hybrid aspen, incorporating height and age data pairs. Initial data were grouped pairwise incorporating all possible pairs; both “forwards” and “backwards” (Borders et al. 1988; Goelz & Burk 1992; Eriksson et al. 1997).

For all models below the following abbreviations were:

H_1 = Height at index age (H_{20}), m; H_2 = Height at total age, m; A_1 = Age for site index, years; A_2 = Tree age, years

The initial step involves producing height/age equations estimating the site specific parameter (H_1) separately for each stand. Then the other parameters were assessed from the 40 sampled aspens.

The models tested were:

A Chapman-Richards function (Richards 1959) proposed by Clutter et al. (1983):

Total age:

$$H_2 = H_1 \times [(1-e^{(\beta_0 \times A_2)})/(1-e^{(\beta_0 \times A_1)})]^{\beta_1} \tag{1}$$

where:. β_0, β_1, are parameters

A Hossfield based model proposed by Cieszewski & Bella (1989):

Total age:

$$H_2 = (H_1 + D + R)/(2 + 4 \times \beta_0 \times A_2^{-\beta_1} /(H_1 - D + R)) \tag{2}$$

where, $D = \beta_0 / K^{\beta}{}_1$, $R = [(H1 - D)^2 + 4 \times \beta_0 \times H_1 / A_1{}^{\beta}{}_1]^{0.5}$, and K, β_0, β_1 are parameters

A model derived by Cieszewski (2001, eq. 21):

Total age:

$$H_2 = H_1 \times ((A_2^{\beta_0} \times (A_1^{\beta_0} \times P + \beta_1)) / A_1^{\beta_0} \times (A_2^{\beta_0} \times P + \beta_1))) \tag{3}$$

where: $P = Z_0 \times (Z_0^2 + (2 \times \beta_1 \times H_1)/ A_1^{\beta 0})^{0.5}$, $Z_0 = H_1 - \beta_2$, and β_0, β_1, β_2 are parameters

Statistical analysis

Data were analyzed by nonlinear regression using the SAS/STAT system for personal computers (SAS Institute, Inc. 2006). A measure of the goodness of fit of the nonlinear regressions was based on the coefficient of determination (Zar, 1999);

$$R^2 = 1 - (SSE/SST\ (corrected)) \tag{4}$$

where: SSE is the sum of squares of the error terms and SST is the total sum of squares.

The performance of the tested models were evaluated using root mean squared error (RMSE), mean error (ME), mean absolute error (MAE), mean percentage of absolute error (MAPE) and residual plots. According to Parresol et al. (1987) MAE provide a clear distinction between examined models.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(Y - \hat{Y}_i)^2}{n}} \tag{5}$$

$$ME = \frac{1}{n}\sum_{t=1}^{n}(Y_i - \hat{Y}_i) \tag{6}$$

$$MAE = \frac{1}{n}\sum_{t=1}^{n}\left|Y_i - \hat{Y}_i\right| \tag{7}$$

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{Y_i - \hat{Y}_i}{Y_i}\right| \tag{8}$$

where: Y_i and $\hat{Y}_i$ are observed and predicted values of heights (Y)

As the curve profile differ even though results of statistic tests are similar, visual examinations are important for the final recommendation of a model. Therefore the residuals for the models (age versus and predicted height versus residuals) and the fitted curves for different site indices overlaid the observed values (age and height) were visually examined.

The validity of the model could be assessed by an independent data set (Kozak & Kozak 2003). However the validation could not be done by using independent data set from plots as the number of available stands was sparse. Instead the prediction of the model was done by a "leave-one-out cross validation" procedure. The entire experiment was left out one at a time and the parameters were estimated for the reduced data set (Nord-Larsen et al. 2009).

Data represent repeated measurements from individual plots and serial correlation can be present. As the aim of the present study was to evaluate models and chose the most appropriate one for practical use in prediction of height and site index and no apparent bias was observed the problem of autocorrelation might be small in this study. However, the autocorrelation doesn't impact the parameter estimates, which is the most important part of the work in this case. From a practical point of view the autocorrelation problem is generally ignored when using models for prediction of height and site index (Diéguez-Aranda et al. (2006a, b); Monserud (1984); Rayner (1991); Diaz-Maroto et al. (2010); Eriksson et al. (1997); Elfving & Kiviste (1997)). Adame et al. (2006) reported independent shapes of site index curves for rebollo oak (*Quercus* pyrenaica Willd.) with and without correction for autocorrelation. If the residuals are corrected for autocorrelation of the data the result might be that problems are hidden within the model and lead to misinterpretation of observed trends (Nord-Larsen, 2006). According to Kozak (1997) autocorrelation does not seriously affect the prediction capabilities. Based on these findings the autocorrelation was not corrected in the present study.

Results

The fitted curves for different site indices overlaid the observed values (age and height) were visually examined (Fig. 2). Model (3) fitted the data from the sampled trees well and the curves reflected the observed data throughout the age interval. The growth curves for model (2) did not follow a typical decrease in height growth with increasing age. The residuals for the models (age versus and predicted height versus residuals) were visually examined and the residuals for model (3) showed the best fit (Fig. 3).

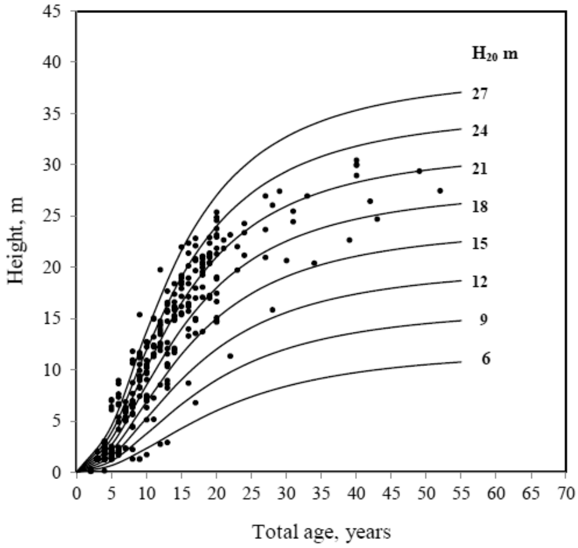

Fig. 2 Site index curves (H_{20}) for hybrid aspen growing at different locations (lat. 55-60º N) n=40 trees. Total age is used.

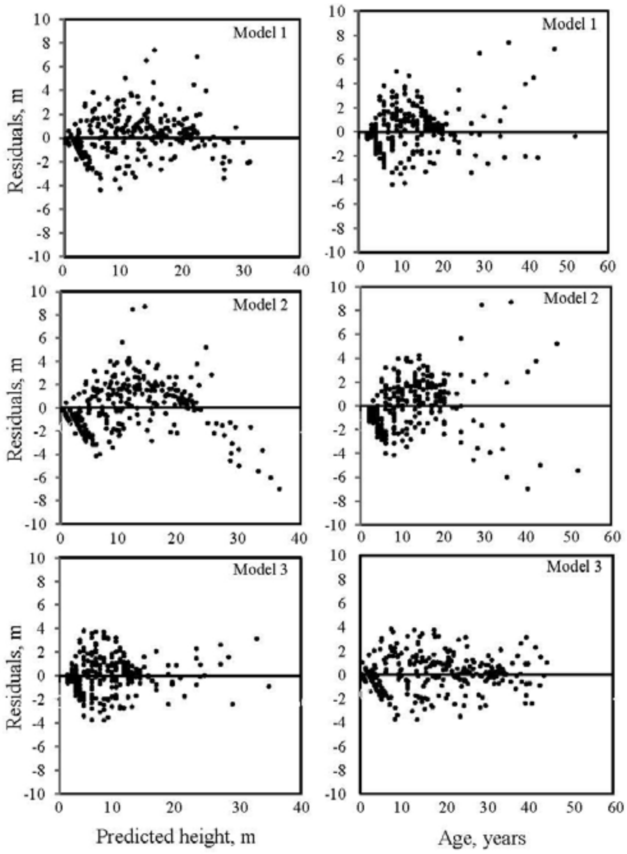

Fig. 3. Residuals of the site growth models for hybrid aspen

The parameter estimates for the tested models are presented in Table 2. Values for the parameters for models 1-3 were derived

using test data. The coefficient of determination (R^2) for all models indicated a good correlation, 98%−99 %, between the fitted curves and the estimated values. Further information about parameter estimates is given in Table 2. Model (3) predicted the heights with the lowest RMSE (1.34 m). Mean residual errors (MRES) between the observed and predicted tree heights were calculated for four age classes: 1−10; 11−20; 21−30 and >30 years (Table 3). All models overestimated the heights for age class 1−10. Model (3) slightly underestimated height for age classes 11−20, 21−30 and >30 years (Table 3). Model (1) seemed to be less flexible with respect to trees in age class >30 and model (2) for all diameter classes. There were small differences in ME for the models, -0.05−0.05 m, with the lowest value (0.02) for model (3) (Table 2). MAE of the site growth models ranged between 0.97 and 1.55 m. Model (3) performed better than the other two models. Model (3) had the best accuracy by the tested models with a MAPE of 9.87%, with 11.62 and 15.64% respectively for models (1) and (2), Table 2. Thus model (3) proved to be the most appropriate. In the validation analyses, "leave-one-out cross-validation", RMSE was slightly larger, 1.38, than for fitted model (3), (Table 2). There were no statistically significant differences in site indices between the soil types indicated by a paired t-test (LSD). Site location had no effect on tree growth.

Table 2. Estimated parameters and standard errors of the algebraic difference approach models (1) – (3)

Model	No of diff.	Parameters	Parameter estimates	SE	RMSE	R^2	ME	MAE	MAPE	RMSE[1]
1	2880	β_0	0.0789	0.0014	1.61	0.98	0.05	1.14	11.62	1.67
		β_1	2.0383	0.0280						
2	2880	β_0	71.3814	1.9049	1.99	0.98	-0.05	1.55	15.64	2.06
		β_1	1.4103	0.0143						
		K	1.0267	0.0291						
3	2880	β_0	2.0381	0.0163	1.34	0.99	0.02	0.97	9.87	1.38
		β_1	4692.5000	147.8000						
		β_3	23.1758	0.1929						

1）Root mean square of the cross-validation procedure

Table 3.Average bias (B), m, according to age classes for models (1)−(3)

Age class (Years)	RES for models			
	No. of obs.	1	2	3
1-10	1602	-0.23	-0.65	-0.07
11-20	1026	0.34	0.92	0.14
21-30	153	0.29	0.56	0.21
>30	99	1.38	-0.75	0.33
Total	2880	0.05	-0.05	0.02

Discussion

Hybrid aspen clones used in the study were mainly planted in the end of 1980. At that period there was an increasing interest in planting trees on abandoned farmland. The output of clones was sparse and even today the commercial clones are almost the same as for 40−50 years ago. The information from the seedling distributors and a report by Christersson (2010) prove that the origin of hybrid aspen stands in the present should be a mixture of sampled clones from 1939 to 1969. Then height curves for the stands represent the site index and the growth of the "top height trees" in the studied hybrid aspen plantations are related to the site productivity. The tree height distribution within a stand is uniform in a farmland compared with forest land. However in the present study the standard deviation for hybrid aspen height and diameter at breast height in the stands show that there are differences within the stands. The overall height and diameter means and deviation also differ for trees in stands (19.9±4.2 m and 19.6±6.5 cm) and top height (22.0±4.3 m and 28.0±8.3 cm) respectively.

The data collected were suitable for constructing curves representing ages up to 50−60 years. Most of the stands had attained a height of between 19 and 24 m when they were 20 years old (H_{20}). In the present study model (3) with a base age of 20 years RMSE was 1.34 and the "leave-one-out cross validation" 1.38. In an overview of site index systems for species in northern California made by Krumland and Eng (2005) RMSE >2 m was presented. Goelz & Burk (1992) studied the RMSE level related to the choice of base age. They found that RMSE decreased with increasing base age e.g. 1.7 at <20 years to 0.8 at 35−50 years of base age. However, in the present study with a mean age of 21 years (range 15−51) and most stands with an age of 18−22 years an RMSE of 1.5−1.6 seems to be within the range mentioned above. Goelz & Burk (1992) recommended a base age less than or equal to the youngest rotation age.

Site index curves (H_{20} m) calculated using our model 3 (based on total age) was compared with Danish curves presented by Jacobsen (1976) (Fig. 4). The curves in the Danish study indicate a faster growth than in the present study. The site "Bon I" corresponds to H_{20} = 21 m and sites Bon II & III were 17 and 13 m respectively. In Figure 4 the site curves for hybrid aspen are compared with data derived from a 42-year-old hybrid aspen stand in a permanent plot (no. 677) in Sweden (Carillo 2001), data from a 30-year-old stand growing on farmland in southern (Lat. 58°57′ N. Long. 14°13′ E.) and a 32-year-old stand in central Sweden (Lat. 62°25′ N. Long. 16°36′ E.) (Elfving 1986 a, b). The data from the study in Sweden correspond to a H_{20} = 22 m, which indicates a medium growth level compared with data

presented in the present study. Møller (1965) presented height values for three stands (15, 19 and 20 years old) in Denmark. Mean heights for 16-year-old hybrid aspen in the Norwegian study (Langhammer 1973) indicate a site index of H_{20} = 24 m, similar to the site index curves in the present study. It is possible that the restricted height of hybrid aspen may be the result of planting inappropriate provenances or clones combined with a wet site, which is not favorable for hybrid aspen growth.

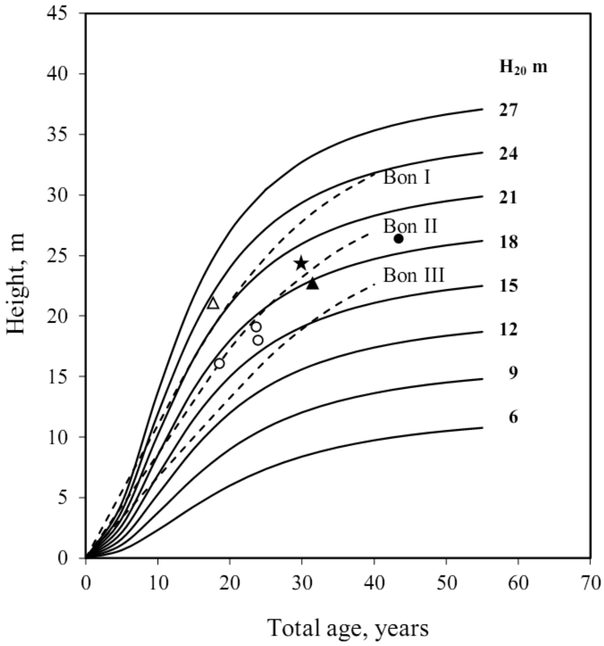

Fig. 4 Site index curves for hybrid aspen (H_{20}) compared with a Danish study reported by Jacobsen (1976) and reported site index curves for hybrid aspen. The symbols represent mean heights from a permanent plot no. 677 (Lat. 58° 57' N. Long. 14° 13' E.) (Carillo, 2001) ●, a stand in southern Sweden (Lat. 55° 54' N. Long. 13° 23' E.)★ and one in central Sweden (Lat. 62°25' N. Long. 16°36') ▲ and from a Danish study (Møller, 1965) ○. The symbol△ represents mean height for a 16-year-old stand of hybrid aspen in a Norwegian study (Langhammer 1973).

Hybrid aspen has the potential to establish rapid and produce good early growth when planted on former farmland in the Nordic countries (Rytter & Stener 2005). Most stands were growing on sediments (light and medium clay). However there were no statistical differences between soil type and H_{20}. Unfortunately no chemical analysis of the soil could be made. Many stands, as indicated by our data, are inappropriately managed or are planted on sites where the physical conditions are inappropriate for the species. The ground must be prepared prior to planting to ensure that competition is restricted during the first two years of tree growth and that plantations are fenced to exclude grazers and browsers. On farmland, the incidence of disease and pests increases substantially with the age of the stand (Møller 1965; Langhammer 1971; Jacobsen 1976; Kasanen et al. 2002).

The practical implications of site index curves are focused on plantations on farmland as there are serious problems in plantations on forest land with damages on the aspen stems caused by wild habitat (mooses (*Alces* alces L.) and roedeers (*Capreolus capreolus* L.)). In practice insufficient attention is often paid to the period between seeding or planting and the age at which saplings reach breast height. Poor aspen growth could be the result of poor site conditions, the use of inappropriate clones, vegetation competition, inappropriate soil treatment or damage caused by wild animals. Better management of the young stand could mitigate some of these problems. However site properties on forest land indicating a rich site e.g. corresponding to site index >G30 (H_{100} = 30 m for Norway spruce (*Picea abies* (L.) Karst.)) are suitable for hybrid aspen. Sites on forest land representing European aspen, >H_{40} = 25 m (Johansson 1996), could be recommended for plantings of hybrid aspens on forest land.

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